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PATENT APPLICATION OF

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ENTITLED

COMPENSATED VARIABLE OPTICAL ATTENUATOR

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COMPENSATED VARIABLE OPTICAL ATTENUATOR

CROSS REFERENCE TO RELATED APPLICATION

This application is a Continuation-In-Part application of United States Patent Application Serial No. 10/430,845, filed May 6, 2003 and entitled VARIABLE OPTICAL ATTENUATOR.

FIELD OF THE INVENTION

The present invention relates generally to optical attenuators and, more particularly, to methods and structures for variable optical attenuation.

BACKGROUND OF THE RELATED ART

Optical networks, e.g., telecommunications networks, are formed of numerous devices. Switches, routers, couplers, (de)multiplexers, and amplifiers are commonplace in networks. These devices must be compatible with one another to function properly, i.e., they must be able to receive and transmit compatible signals. For some networks, this compatibility requires that network devices operate on signals within a specified intensity range - a constraint that makes network power level management quite important.

Systems designers often rely upon optical attenuators to properly manage network power levels. These attenuators can be stand-alone or integrated with other devices to controllably set signal intensities. Intensity can be controlled between serial devices like amplifier stages, between parallel devices like switching banks, and even within a single optical device, like an attenuator integrated into an

existing wavelength division multiplexing (WDM) device to normalize channel intensities.

For many applications, attenuators are fabricated by suppliers that, in turn, supply optical device manufacturers who assemble the network appliances (switches, routers, etc.). Since different networks may be optimized for different signal intensity levels, suppliers will often make a batch of identical optical devices and then tailor some of them to meet the needs of the device manufacturer, i.e., the particular network.

Variable optical attenuators (VOAs), where the amount of attenuation is adjustable, are known. VOAs are commonly formed of a blocking structure (like a movable absorber or partially reflecting structure) disposed in a free space region between an input waveguide and an output waveguide. The position of the blocking structure within the free space region determines the amount of attenuation. Shutters, mirrors, prisms, and even liquid crystal structures have been used as blocking structures.

Another attenuation method used misaligns fibers via a mechanical spring, a technique that results in significant temperature-dependent instabilities. Axial separation between fiber ends has also been proposed, though the methods require a large displacement and expensive moving parts.

In other forms, people have developed continuous wave attenuation devices formed of two waveguides twisted and fused together to form a bulk switching/attenuation region. Some of these devices also use thermal elements for selective switching and attenuation control. Still others have developed VOAs that use a Faraday rotator or pockel cell-like structure to attenuate based on polarization state.

While these techniques may be useful for some applications, they introduce undesirable manufacturing costs and complexity of operation. Furthermore, the devices are bulky and incompatible with networking environments where space is a major concern. They are also difficult to install within a network and, therefore, can result in substantial network downtime or slowdown. Perhaps even more important, many of these known VOA devices introduce a substantial amount of unintentional and undesirable loss. For example, insertion loss and polarization dependent loss (PDL) greatly limit operation of known VOA devices. Further, known VOAs also exhibit stability problems malfunctioning if moved or jostled during operation. Additionally, changes in temperature in the VOAs can introduce undesirable effects. Finally, as VOA's provide finer control of attenuation, error from any source will become increasingly undesirable.

Some VOA devices utilize signal sampling and feedback to provide precise attenuation control. However, signal sampling methods are costly are require significant space for implementation. Moreover, sampling transducers can be affected by changes in temperature such that temperature can still affect attenuation levels of systems that employ sampling transducers.

It is, therefore, desirable to have VOAs that are not overly bulky, do not use extra components, such as partially reflecting elements, sampling transducers or thermal switches, are lower in cost to fabricate, and operate with less loss and higher stability.

SUMMARY OF THE INVENTION

An electrically variable optical attenuator and associated methods are disclosed. In one aspect, the attenuator includes at least one sensor that provides a sensor output with respect to a

variable that affects attenuation. Methods of characterizing the attenuator include obtaining a set of attenuation/sensed variable data, and generating a relationship (such as a look-up table or mathematical function) relating the sensed variable to the attenuation. Aspects of the invention also include characterizing the control input/attenuation output to be related by a selected mathematical function.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 is a block illustration of an example optical attenuation system having a variable optical attenuator disposed between a laser and a receiver.

FIG. 2A is an illustration of one embodiment of an example optical attenuator showing a first waveguide and a second waveguide disposed on a base member.

FIG. 2B is an illustration of the structure of FIG. 2A showing waveguide supports.

FIGS. 3A and 3B are cross-sectional views of an example optical attenuator including a top member and depicting separate attenuation conditions each.

FIGS. 4A and 4B are cross-sectional view of another example optical attenuator including a top member and depicting separate attenuation conditions each.

FIG. 5 is an exploded view of another example optical attenuator.

FIG. 6 is a cross-sectional view of the structure of FIG. 5 (assembled) looking along lines BB of FIG. 5; the view showing example positions of a movable cantilever portion of a waveguide.

FIG. 7 is a cross-sectional view of the structure of FIG. 5 (assembled) looking along lines BB of FIG. 5; the view showing other example positions of a movable cantilever portion of a waveguide.

FIG. 8 is an illustration of the structure of FIG. 5 assembled.

FIG. 9 is a cross-sectional view similar to that of FIGS. 6 and 7, but showing another example optical attenuator.

FIG. 10 is a cross-sectional view similar to that of FIGS. 6, 7, and 9 but showing another example optical attenuator.

FIG. 11 is an illustration of a variable optical attenuator array.

FIG. 12 is a block diagram showing an example closed-loop control system for operating an optical attenuator.

FIG. 13 is a block diagram showing an example power back-up system for operating an optical attenuator.

FIG. 14 is a diagrammatic view of a method of characterizing a VOA in accordance with an embodiment of the present invention.

DETAILED DESCRIPTION OF PREFERRED EXAMPLES

While preferred examples and numerous alternative thereto are provided below, it will be appreciated by persons of ordinary skill in the art that these are merely examples and not intended to be exhaustive. On the contrary, the teachings herein may be used in many optical devices. Further, while the descriptions provided below are generally in the context of variable optical attenuation, the teachings herein may be used to move waveguides for other purposes, as will be apparent to persons of ordinary skill in the art. The teachings herein may also be used to correct for or induce misalignment between waveguides

for purposes other than attenuation in structures other than those exemplarily shown. Further, while electrically driven actuators in the form of electrostatic actuators are described in most examples, other electrically driven actuators may be used in any of the disclosed examples. Electrically driven actuators receive an electrical signal to actuate movement of a waveguide. Examples include electrostatic, electrothermic, and electromagnetic actuators, though persons of ordinary skill in the art will know of other electrically driven actuators, including other electromechanical actuators.

FIG. 1 shows an example laser system 100 with an input optical signal traveling on an input waveguide 102 coupled to an output optical signal traveling on an output waveguide 104 via a variable optical attenuator 106. The input optical signal may be from a diode laser, gas laser, amplifier, transponder, or other laser or optical source. The input optical signal may be an information carrying laser signal or, alternatively, a single-frequency laser energy, pulsed or continuous-wave. The input optical signal may be coupled to the variable optical attenuator 106, for example, through an optical fiber. The variable optical attenuator 106 is controlled by a controller 108.

The variable optical attenuator 106 receives the input optical signal and attenuates that signal under control of the controller 108. The variable optical attenuator 106 is capable of providing an output optical signal that may have a range of desired intensities. Common telecommunication applications require 0 dB to 20 dB attenuation. With the present examples, 40 dB or more attenuation may be achieved. The controller 108 determines the amount of attenuation provided by the variable optical attenuator 106. In an example, the variable optical attenuator 106 includes two optically, coupled waveguides at least one of which is movable relative to the other. The

controller 108 provides a control signal to an electrically variable actuator (EVA) 110 in the variable optical attenuator 106 to adjust, set, and/or determine the position of the movable waveguide(s). If the electrically variable actuator is an electrostatic actuator, the controller 108 provides a drive voltage to actuator electrodes. The movable waveguide(s) moves under an electrostatic force created by the electrodes. The EVA 110 may be an electrothermic or electromagnetic actuator, as well. An electrothermic actuator receives an electrical control signal from the controller 108 and creates a thermal change within the attenuator 106, for example, by heating an element on a movable waveguide causing an expansion that deflects that waveguide. An electromagnetic actuator is one that converts an electrical signal into a magnetic force, which then moves the waveguide(s).

FIG. 2A illustrates a portion of an example optical attenuator 200 (See FIGS. 3A and 3B) that may be used as the variable optical attenuator 106. The optical attenuator 200 is a variable optical attenuator including a base member 201 supporting two waveguides 202, 203, in the form of optical fibers in the illustrated example. Silicon is an example material for the base member 201. The first waveguide 202 has a base portion 204 and a movable cantilever portion 205 with a terminus 206. The second waveguide 203 has a base portion 207 and a cantilever portion 208 that may be movable or fixed. A terminus 209 is at an end of the cantilever portion 208.

In the un-actuated condition illustrated, the terminus 206 and the terminus 209 are axially aligned for maximum waveguide-to-waveguide coupling of energy. Alternatively, the termini 206, 209 may be misaligned in the un-actuated position.

The cantilever portions 205 and 208 extend over a recess 210, which may be formed in the base member 201 through a

photolithographic definition and chemical etching process, for example. With the cantilever portions 205 and 208 suspended over the recess 210, one or both of the termini 206, 209 may be freely moved. In an embodiment, cantilever portions 205 and 208 are formed from substantially identical optical fibers made of fused silica, a flexible material with a restoring spring force that biases the structure to its original position. Example fibers include single-mode Corning SMF-28® fibers with angled or flat end-faces at the termini.

The base portions 204 and 207 are affixed to first and second supports 211 and 212, for example, using a bonding material (not shown). The base member 201 may be fabricated from fused silica wafers to precisely match the expansion coefficient of the waveguides 202 and 203, if they are also formed of fused silica. The supports 211, 212 may be formed from silicon wafers with anisotropically etched v-grooves 214 and 216 (best seen in FIG. 2B) that receive the base portions 204 and 207. The v-grooves 214 and 216 may alternatively be mechanically formed. Axially aligning the v-grooves 214 and 216 aligns the termini 206 and 209 in the un-actuated position. The v-grooves 214 and 216, however, may be misaligned so that the two waveguides 202 and 203 are axially misaligned in the un-actuated position. when axially aligned, the waveguides 202 and 203 have a maximum coupling; misaligning them produces a un-actuated, attenuated coupling.

In the illustrated example, the device 200 is a dual cantilever device in which one or both of the cantilever portions 205 and 208 may be moved to attenuate a signal propagating from one to the other of the waveguides 202, 203.

FIGS. 3A and 3B show a cross-sectional view of the assembled optical attenuator 200 having the base member 201 and a top member 222 attached thereto. The top member 222 is substantially

identical to the base member 201. The top member 222 includes a recess 224 with a third electrode 226 similar to the electrode 218. The recesses 224 and 210 form a cavity 225, which in the illustrated example has a uniform depth. The third electrode 226 and a fourth electrode 228 on the cantilever portion 208 form a second electrically variable actuator. FIG. 3B shows the structure of FIG. 3A with the two cantilever portions 205 and 208 deflected in opposite directions towards their electrostatic actuator electrodes 218 and 226, respectively, to achieve a desired attenuation of a signal propagating between the two. In other words, FIG. 3A shows a first optical attenuation position where there is the least amount of attenuation, and FIG. 3B shows a second optical attenuation position where the system has been adjusted to achieve a desired amount of attenuation.

In FIG. 3B, the termini 206 and 209 are optically coupled but misaligned a distance, d, thereby causing optical attenuation. The attenuation between the optically coupled termini 206 and 209 varies nonlinearly as a function of axial offset, i.e., offset from the coaxially aligned position. In the preferred example, the termini 206 and 209 are always optically coupled for energy transfer.

FIGS. 3A and 3B provide example attenuation conditions. Actuation of the cantilever portion 205 is achieved by a first electrode 218 in the recess 210 and a second electrode 220 on the cantilever portion 205. The electrodes 218 and 220 form a first electronically variable actuator. The first electrode 218 may be deposited into the recess 210, and the second electrode 220 may be deposited around a cladding of the cantilever portion 205. The cantilever portion 205 may have a narrowed fiber section, that is, one with a reduced cladding or no cladding, which may increase fiber flexibility. The cantilever portion 205 may also have an expanded core. In the illustrated example, the

cantilever portions 205 and 208 are geometrically matched in length and diameter to cancel temperature and acceleration errors.

In operation, a control device like the controller 108 provides an electrostatic actuator drive signal from the electrode 218 to electrode 220 to move the terminus 206 into the recess 210. Another drive signal may be applied to the electrode 226 and the electrode 228 for moving the cantilever portion 208 into the recess 224. The two drive signals may be a common drive voltage, moving each cantilever portion 205, 208 in equal magnitude and opposite directions. Of course, the two drive signals may be different, as well. In an embodiment, the drive signals are pulse-width modulated (PWM) voltages. Furthermore, the drive signals may be derived from a look-up table that stores drive signal voltage versus desired attenuation values. A calibration may be performed on the assembly 200 to form the look-up table. Further still, as discussed additionally below, the drive signal may be derived from a feedback loop, where the drive signal value is determined in response to a measured attenuation value or a deflection-dependent measured parameter value, such as an electrical value like capacitance, voltage, current, inductance, or frequency.

FIGS. 4A and 4B show an example structure 200' similar to structure 200 of FIG. 3A and 3B, and thus like reference numerals are used, in prime form. The example of FIGS. 4A and 4B have a base member 201' with a variable depth recess 210' and a top member 222' with a variable depth recess 224'. The recesses 210' and 224' form a cavity 225' having a variable depth. A variable depth cavity may lower the voltage magnitude for a given deflection.

FIG. 5 illustrates a portion of another example optical attenuator 300 formed of a base member 302 having two v-groove supports 304 and 306 and a recess 308. The recess 308 has two side

walls 310, 312. Electrodes 314 and 316 are disposed on the side wall 310, 312, respectively, adjacent a cantilever portion 318 of a waveguide 320. These electrodes 314 and 316, as well as the other similar electrodes described herein, may be electrically insulated from direct contact with the base member 302. In the illustrated example, the waveguide 320 is an optical fiber having a terminus 321 and a conductive layer 322 that at least partially extends from a base portion 323 held in place on the support 304. Two additional electrodes 324 and 326 are positioned at an opposing end of the recess 308, adjacent a cantilever portion 328 of an optical fiber 330, which also has a terminus 331 and a conductive layer 332 and a base portion 333 held in place on the support 306. The conductive layers 322 and 332 may be formed by applying or depositing a metal layer around the fibers 320 and 330, respectively. An electroless plating process using a chemical precursor step or a physical deposition process may be used. The optical fibers 320 and 330 are positioned with their cantilever portions 318 and 328 extending over the recess 308.

A top member 334 is also shown in FIG. 5. The top member 334 includes a recess 336 with two side walls 338, 340. The recess 336 and the recess 308 form a cavity 342 (see FIG. 6) within which cantilever portions 318 and 328 may be deflected. The cavity 342 may be diamond-shaped in cross-section or it may take on other shapes. The base member 302 and the top member 334 may be bonded, fused, clamped, or otherwise mounted together to form the unitary structure depicted in FIG. 8. Electrodes 344, 346 are formed on the side walls 338, 340, respectively, to operate on the cantilever portion 318, as with the electrodes 314 and 316. Other electrodes 348 and 350 are formed in the recess 336 to operate on the cantilever portion 328, as with the electrodes 324 and 326.

The top member 334 also includes v-groove supports 352 and 354, which combined with supports 304 and 306, enclosing base portions 323 and 333 of the optical fibers 320 and 330, respectively.

An example of operation of assembled parts of the device 300 is partially shown in FIG. 6, a cross-section view from the terminus 331 of waveguide 330 taken along lines BB of FIG. 5, and showing the terminus 321 of the optical fiber 320. The device 300 uses multiple lateral steering electrodes to control waveguide position. The electrodes 314, 316, 346 and 344 are adapted to deflect the optical fiber 320. In illustrated example of FIG. 6, 320' represents the fiber 320 deflected in a first direction, such that a fiber core 356 is offset from an un-actuated position a distance, d'. 320" represents the fiber 320 deflected in a second direction, such that the fiber core 356 is offset from an un-actuated position a distance, d". The fiber 320 may be deflected in different directions than those shown. FIG. 7, for example, shows the optical fiber 320 deflected along vertical directions into positions 320' and 320". Using adjacent electrodes, such as illustrated in FIG. 7, to move a waveguide results in significantly reduced electrostatic drive signal values. In FIGS. 6 and 7, the fiber 320 is showing moving in first and second directions (toward positions 320' and 320") that are parallel. There is a full range of movement into different directions, however. The device 300, as illustrated, includes the plurality of electrodes 314, 316, 344, 346 and 324, 326, 348, and 350 where some may receive an identical or different drive signal. Furthermore, the drive signal(s) may include a fixed bias voltage to achieve a desired un-actuated position between the fibers 320 and 330, for example, a "full-on," "full-off," or "partially-attenuated" position.

The deflection of the optical fiber 330 would be similar to the examples provided in FIGS. 6 and 7 with respect to the fiber 320.

The optical fiber position 320 of FIGS. 6 and 7 may be a non-deflected, axially-aligned position, whereas the positions 320' and 320" may be misaligned positions. Furthermore, while the v-groove pairs 304/352 and 306/354 are axially aligned, the pairs may be axially misaligned thereby building in an offset into the device 300.

The base portion 323 of the optical fiber 320 is placed in the supports 304 and 352. Support 304 has an electrode 360 that contacts the metal layer 322. Conductive pads 362 and 364 may be used to electrically excite the layer 322. The electrodes 314 and 316 are connected to conductive pads 366 and 368 respectively. To deflect the optical fiber 320 downwards, for example, a drive signal may be applied across the conductive pad 362 (and/or 364) and one or both of the conductive pads 366 and 368. The top electrodes 344 and 346 are connected to conductive leads 370 and 372, respectively, when the top member 334 is formed on the base member 302. As shown in FIG. 8, these leads are exposed in the assembled device 300. A voltage may be applied across pad 362 (and/or 364) and the lead 370 and/or the lead 372 to deflect the optical fiber 320 upwards. Deflection of the optical fiber 330 is achieved in a similar manner using leads 374 and 376, as well as conductive pads 378, 380, 382, and 384.

FIG. 9 illustrates a cross-sectional view of another optical attenuator 400 having a cavity 402 formed of six walls 404, 406, 408, 410, 412, and 414. A base member 416 and a top member 418 form the device 400. In the illustrated example, an optical fiber 420 with terminus 421 is shown in three different positions, 420, 420', and 420". Electrodes 422, 424, 426, and 428, along with a conductive electrode (not shown) on the fiber 420 are used to form an electrically driven actuator for deflecting the fiber 420. Control may be achieved in a similar manner to that described above with respect to FIG. 5.

FIG. 10 illustrates a cross-sectional view of another optical attenuator 500 having a cavity 502 formed of three side walls 504, 506, and 508. A base member 510 and a top member 512 form the device 500. In the illustrated example, an optical fiber 514 is shown in three different positions, 514, 514', and 514". Electrodes 516, 518, and 520, along with a conductive electrode (not shown) on the fiber 514 are used to form an electrically driven actuator for deflecting the fiber 514. Control may be achieved in a similar manner to that described above with respect to FIG. 5.

With the above examples, the use of a symmetrical pair of cantilever waveguide portions that are freely deflectable in different directions means that less deflection of each waveguide is needed to achieve a given attenuation. As a result, shorter waveguide cantilever lengths, higher resonant frequency, and faster response times may be achieved. Also, common mode cancellation of acceleration deflection induced errors may be achieved and temperature induced errors reduced. Furthermore, freely supported, cantilevered movable portions have little or no hysteresis, because there is no bottoming or rolling contact area, thereby avoiding rubbing and sliding that plagues other devices.

Other geometries may be used for the cavities and recesses described. For example, the recesses may be curved in cross-section, i.e., semi-circular in shape. Also, alternative electrode geometries or patterns may be used. Electrode geometries and control schemes may be used to increase the amount of deflection before an unstable electrostatic snap down position is reached, for example.

Snap down is a condition whereby a fiber end is uncontrollably deflected until it actually moves into direct contact with the pulling electrode. The condition results from the following. The

electrostatic force between a coated optical fiber and an adjacent electrode increases approximately as the inverse square of the gap between the two. The restoring spring force in an optical fiber increases linearly with deflection, however. As the drive voltage increases and the gap between a fiber and an adjacent electrode decreases, an unstable point is reached where the exponentially increasing electrostatic force overpowers the linearly increasing spring force in the fiber, and the fiber suddenly snaps-down onto the pulling electrode.

The snap down point may be adjusted by replacing the electrodes within the recesses with multiple electrodes that receive different drive voltages. A suitable interlaced, or interdigital, electrode pattern was described in a co-pending application U.S. Serial No. 10/261,111 filed on September 30, 2002 entitled "VARIABLE OPTICAL ATTENUATOR", which is incorporated herein by reference.

Numerous other alternatives will now become apparent to persons of ordinary skill in the art. For example, a dielectric oil fill material may also be used in the cavities of the devices 200, 300, 400, and 500 to reduce drive voltage, dampen vibration, and eliminate end face reflections. The presence of environmental vibration, up to typically 2 kHz, may cause the cantilever portions to vibrate at their resonant frequencies. The length of the cantilever portion, i.e., extending from a base portion, may be set to prevent such resonance. With a fill material, the system may be critically damped to eliminate resonance allowing for longer aspect ratios for the cantilevered portions.

With or without a fill material, it may be desired to provide an angle on the terminus for each movable portion. For example, and 8° angle may be used to reduce end face reflections back into the fiber. Further, an antireflection coating on each terminus may also be used to reduce transmission losses.

FIG. 11 illustrates a variable attenuation array device 600 formed of individually controlled variable optical attenuators 602, 604, and 606. The array device 600 is used to set similar or dissimilar attenuation levels in three different optical communication paths. A single controller can individually operate each of the devices 602, 604, and 606. The array device 600 may include additional or fewer optical attenuators. Each of the attenuators 602, 604, or 606 may represent any of the devices 200, 300, 400, 500, or others described herein.

FIG. 12 shows a block diagram of an example processing system 700 for operating an optical attenuator. A control block 702 receives an input signal or command by which the desired attenuation level is set. The control block 702 may include memory and readable and executable software routines. The control block 702 may store or access a look-up table of data representing drive voltage versus attenuation levels. A signal block 702 is provided to an EVA (electronically variable actuator) and VOA (variable optical attenuator) block 704. The control block 702 controls the EVA and VOA block 704, which may include the assemblies 200, 300, 400, and/or 500. The block 704 may further include multiple actuators. The block 704 receives an optical signal via an input waveguide 705a and has an output waveguide 705b that may connect to an optional optical detector block 706 that measures the optical output power and provides a signal to a measurement block 708.

Using the system 700 with the optical attenuator 200, for example, the movable portion 205 is deflected by a DC signal applied to the electrode 218. If attenuation is controlled by an electrical parameter like capacitance, the control block 702 would provide an AC signal across the electrode 218 and the electrode 220, via the EVA and VOA block 704, to detect a detectable value of the electrical parameter. That

is, the AC signal is used to detect the actual capacitance between the electrodes 218, 220. Capacitance, current, inductance, frequency, and other electrical parameters may be detected in a similar manner. Thus, a single electrode pair may be used to deflect a movable portion of a waveguide and may be used to determine or sense a detectable value of an electrical parameter related to the position of that movable portion, for feedback control. Alternatively, separate electrodes may be used for movement and for detections.

In one configuration, the detectable value from block 704 is provided to the measurement block 708, which may derive an actual parameter value (e.g., calculate a capacitance value in farads) or the block 708 may compute a distance or attenuation based upon the detectable value. The measurement block 708 may be part of a controller or processor that includes other blocks shown in FIG. 12. The detected value of the electrical parameter is provided by the block 708 to the control bock 702, which determines if the detected value equals the desired electrical parameter value. The control block 702 may also determine if a desired misalignment or position value has been achieved If the two values do not match, the control block 702 will direct the block 704 to move one or both movable portions accordingly until the two values agree. If the two values do match and the desired attenuation is not achieved - a determination that could be made with the use of a separate photo detector as illustrated by the block 706 and having an input provided to the control block 702 - then the control block 702 can adjust the termini position in the system until the desired attenuation is achieved. The control block 702 may also update its look-up table data in such cases, as they would suggest that the stored attenuation versus electrical parameter data is no longer accurate.

FIG. 12, therefore, illustrates a system that performs closed loop position stabilization on a movable cantilever portion of an optical waveguide. Numerous alternatives to the control system 700 will be known to persons of ordinary skill in the art. By way of example, the measurement block 708 may measure temperature and, in conjunction with the control block 702 or alone, provide a temperature compensation coefficient that is used in determining control parameters necessary for a given desired optical attenuation. For illustration, a sensor 710 is shown coupled to the VOA. Sensor 710 can be any suitable sensor for sensing any condition that may affect the attenuation of the VOA in any manner. Thus, a suitable sensor 710 could be used to sense temperature, acceleration, vibration, and/or pressure using suitable sensing transducers. In embodiments where sensor 710 includes a temperature sensor, sensor 710 is preferably thermally coupled to the VOA. Sensor 710 could be a Resistance Temperature Device (RTD), thermocouple, thermistor, temperature sensitive capacitor, or any other suitable type of temperature sensor disposed adjacent or even fabricated integral with the VOA.

For embodiments where the sensor is fabricated integral with the VOA, a number of fabrication options may be employed. for example, a thin film resistor could be deposited upon the VOA. Alternatively, a temperature-sensitive resistor could be diffused into the VOA substrate. In yet another embodiments, a temperature-sensitive capacitor could be fabricated on the VOA substrate. In these cases, the electrical property of the sensor (e.g. capacitance of a temperature sensitive capacitor) is monitored by measurement block 708 and/or control block 702 such that any temperature-induced effects on attenuation can be ameliorated. This can be accomplished by causing control block 702 to increase or decrease the control signal provided to

EVA 704 based upon the magnitude and sign of the temperature difference measured by the temperature sensor from a standard temperature condition. The precision of the temperature correction can vary depending on the needs of each application.

Wavelength Dependent Loss (WDL) can also be compensated in accordance with embodiments of the present invention. FIG. 12 shows an input wavelength 712 entering WDL block 714, which provides an indication of input wavelength(s) to control block 702. Embodiments of the present invention can utilize WDL compensation alone; WDL compensation with temperature compensation; temperature compensation alone; and any combinations of WDL compensation, temperature compensation and/or other types of compensation using one or more sensors disposed proximate and/or within the VOA. The wavelength signal provided by block 714 may be compared to a reference wavelength and the comparison used to also adjust the position of the movable cantilever portion.

The processing of FIG. 12 may be achieved entirely on an optical attenuator chip that has a control circuit and memory storage, or the processing may be from external components. It will be understood by persons of ordinary skill in the art that the processing shown may further include additional processing blocks and/or an input device like a keyboard, touch-screen or other manual input or user-interface device, as well as an output device like a computer monitor.

FIG. 13 shows an alternative processing system 800 of an optical attenuator. As illustrated, a control block 802 has memory storage or access and readable and executable software routines for determining a desired drive signal for deflecting a movable portion of a waveguide, when the block 802 supplies that drive signal to an EVA block 804. The block 804 deflects a waveguide or multiple waveguides

within a VOA block 806. An input waveguide 807a and an output waveguide 807b are shown coupled to the VOA 806.

FIG. 13 further includes a power backup block 808 that ensure a constant drive signal voltage is applied to the block 804 such that, if the power to the control block 802, or to the block 804, is removed for some reason, the power backup block 808 will power the block 804, retaining the drive signal to the actuator electrode(s), to retain the terminus and movable portion in their pre-fault positions. The processing of FIG. 13 is a hold-in-place control that maintains optical attenuation at a given value, even upon fault. Alternatively, the system block 800 may reset the attenuation position of the movable waveguide(s) to a steady-state position, for example a "full-on," "full-off," or "partially-attenuating" position.

The power backup block 808 may be achieved in known ways. For example, it may be a battery backup or any power source that supplies power under a controlled slow leakage, such as a super-capacitor. Various response times may be used for the power backup block 808, however, in the preferred example, the power backup block 808 is continuously coupled to the EVA block 804 via electrical connection 810 so that the terminus position does not change upon fault.

FIG. 14 is a diagrammatic view of a method of characterizing a VOA in accordance with an embodiment of the present invention. Method 900 can be performed to characterize the VOA with respect to any variable, such as temperature. Further, method 900 can be repeated to characterize the VOA with respect to additional variables. This iteration should be nested unless the parameters being characterized are completely independent of each other. For example, method 900 could be executed a first time to characterize for temperature, and subsequently performed to characterize for wavelength

dependent loss (WDL). The method begins at block 902 where one or more extraneous variables are determined. Determining variables can include measuring the extraneous variables, maintaining such variables at a constant level, or setting such variables to a desired setting. For example, when the VOA is to be characterized with respect to temperature, one example of determining an extraneous variable (any variable that is not the subject of the characterization) is by holding a single wavelength intensity at some fixed setting. At block 904, the characterized variable is set or measured at an initial setting. At block 906, the VOA attenuation level is measured. At block 908, the variable that is the subject of characterization is varied and measured. An example of step 908 could be simply increasing VOA temperature during temperature characterization. At step 910, the method checks whether the variable has been varied enough to complete the characterization. If characterization is not yet complete, control returns to block 906 where the attenuation is measured and recorded. This process continues until characterization has spanned a suitable range of the variable with suitable intervals.

At block 910, the recorded pairs or attenuation level/measured variable are used to generate a characterization relating VOA attenuation to the measured variable. Preferably, this characterization is used for the range of the variable for which characterization has been done. However, embodiments of the present invention include extrapolating the characterization to variable ranges beyond that experienced during characterization. The characterization can include the generation of a look-up table, and/or the calculation of coefficients for a mathematical function that can approximate the attenuation level variance as a function of the characterized variable. Once the characterization is complete, changes in the characterized

variable can be compensated effectively. In embodiments where method 900 is performed multiple times to characterize a plurality of variables, it is contemplated that the look-up table could have any suitable number of dimensions to accommodate all of the characterizations. For example, a VOA characterized for temperature and WDL may have a two-dimensional look-up table such that an input wavelength and temperature could be used to obtain an VOA attenuation compensation level.

Although the description of FIG. 14 has focused on characterizing the VOA for a given variable, such as temperature, the method can also be used to measure the response of the VOA to varying control inputs, in order to fit any desired function. For example, the control/attenuation can be characterized to any curve. The attenuation could be a linear function of the control input, a logarithmic function of the control input, an exponential function of the control input, or any other desired arrangement. Preferably, the attenuation level is characterized in terms of decibels. As defined herein, attenuation in decibels (dB) = $10\log_{10}(P_{out}/P_{in})$ and attenuation in % = $(P_{out}/P_{in})*100\%$.

One example of the input/output characterization is as follows. Perhaps an uncharacterized VOA provides 50% of its output span for 75% of its control input span. A transfer function resulting from the characterization of the output from the control input can correct for the nonlinearly of input to output. The transfer function can drive the VOA to the 50% output state when 50% on the control input is supplied. Again, this correction can be done using a look-up table, or a mathematical fit, as appropriate.

The characterization can be performed on a device level, and/or on a model level. For example, each device could be characterized prior to installation and/or during manufacturing. Then,

device-specific information could be used for compensation. Additionally, model-based information could be derived during manufacture to provide at least some characterization for all devices of that model type.

Compensation calculations utilizing the characterization information can be performed by any suitable processing device located in or proximate the VOA, or in any suitable external device. Additionally, the processing device can be provided with an anticipated variable value, such as wavelength, temperature et cetera, such that the processing device can provide compensation without having to receive any sensor input.

Although certain apparatus constructed in accordance with the teachings of the invention have been described here, the scope of coverage of this patent is not limited thereto. On the contrary, this patent covers all embodiments of the teachings of the invention fairly falling within the scope of the appended claims either literally or under the doctrine of equivalents. For example, while embodiments of the present invention have been described with respect to compensating an electrically variable optical attenuator for variables that affect attenuation, the present invention is applicable to any MEMS-based optical device for which can be affected by such variables. Accordingly, the present invention is useful for devices such as MEMS-based optical switches and MEMS-based optical multiplexors.